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Case Study Of Uninterrupted Rooftop Solar PV Implementation Strategy In Remote And Isolated Regions

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ABSTRACT

Equitable electricity access is still a challenge in the more isolated and remote parts of Indonesia, where electricity access is geographically limited, operationally expensive and heavily dependent on highly emitting diesel power plants. In this study, a occupational health and safety-compliant implementation strategy of household rooftop PV systems is analyzed to enable energy transition and decarbonization using tiered load scenarios based on household size and efficient appliance profiles. The results show a daily energy demand ranging from 2.66–5.71 kWh/day and a required PV capacity between 0.79 and 1.69 kWp. From an economic perspective, rooftop PV LCOE without battery storage is estimated at Rp 1,475–1,485/kWh, while the hybrid PV-BESS configuration ranges from Rp 2,753 to 2,772/kWh. The battery option, while more expensive, is still relevant for regions with high nighttime demand, unreliable supply or for off-grid operation. In Scenario 5 with $\boldsymbol{N = 3\ people}$*, rooftop PV becomes increasingly competitive at community scale, with LCOE declining to approximately Rp 2,217/kWh (for 50 households), well below diesel-based power supply costs of about Rp 4,791/kWh. Second, community-scale PV can avoid more than 81.6 ton* CO_2*e per annum by replacing diesel generation. The implementation of PV rooftop in remote and isolated regions must comply with the occupational health and safety aspect as a core requirement, especially for DC protection, grounding, quality of connector, roof structural integrity, and operation certification.*

Keywords: *Renewable Energy, Solar Photovoltaics, Rooftop PV, Energy Transition, Household Energy Demand*

INTRODUCTION

Progress has been made in providing equitable access to electricity in Indonesia. However, the problem of electrification in the remote and isolated regions that are part of the frontier, outermost and disadvantaged region is not solved (Kautsar Fattah et al., 2025). The total household electrification rate at the end of 2023 was 99.78-99.79% with 81,556,202 households electrified and the total village electrification rate was around 99.83-99.85%. Regardless, there are still around 185,662 households that are not electrified and the problem is in the region with difficult geographical conditions to be reached (Kementerian ESDM, 2024). Indeed, as of 2025, there were still 10,068 priority places without electricity, covering about 5,700 villages and 4,400 hamlets, with the highest numbers in Papua, Maluku and Nusa Tenggara (Media Indonesia, 2025; Setiawan, 2026). The data show that the national electricity challenge is no longer just about the access ratio, but also about how to deliver electricity that really reaches isolated and remote regions reliably, affordably, and sustainably.

In such conditions, there are still many isolated and remote regions that use Diesel Power Plants (PLTD) as the main source of electricity. This dependence presents significant

challenges because the operational costs of PLTD are typically high owing to fuel consumption, logistics of delivery to islands or remote regions, and considerable maintenance costs. In addition, the electricity consumption per capita Indonesia in 2023 reached around 1,337 kWh or an increase of 14% compared to 1,173 kWh per capita in 2022, indicating that the energy needs of the community continue to increase (Jayawijaya, 2024; Umiyan, 2024). The dependence on diesel is getting more expensive and environmentally cumbersome with the increasing demand for the product. This system produces high greenhouse gas emissions and is not in line with the national energy transition agenda. This means that isolated and remote regions need electricity supply solutions that are more flexible, cleaner and more suited to local conditions.

Based on previous literature, the implementation of rooftop solar Photovoltaics (rooftop solar PV) in isolated and remote regions shows that this technology is most effective when designed according to local conditions, both in terms of solar radiation potential, household load patterns, and community investment capabilities (Fifianny & Setiabudy, 2025). Therefore, technical and economic analyses must be carried out simultaneously to ensure the system is truly feasible to implement. Several studies also confirm that in areas difficult to reach by the PLN grid, centralized solar power plants or rooftop solar power plants can be a realistic electrification solution, but their success is highly dependent on capacity design, operational reliability, and the suitability of the financing scheme (Fifianny & Setiabudy, 2025; Riawan et al., n.d.). In this context, an approach that incorporates aspects of safety, professional ethics, and social acceptance is crucial, because energy projects in the isolated and remote regions are not only about building power plants, but also ensuring that the technology is safe, transparent, and truly meets community needs (Rizkiawan et al., n.d.).

One of the most relevant options is the residential rooftop solar PV system, as this technology is modular, can be installed in stages, and is suitable for serving the needs of small to medium-sized households. The existing policy framework, MEMR Ministerial Regulation No.2/2024, indicates that rooftop solar PV is for self-consumption, not reliant on schemes to export to the grid (JDIH Marves, 2024; Solar Surya Indotama, 2024). The load profile, the capacity of the panel and the needs of energy storage should also be carefully considered in the system design to maintain the uninterrupted supply. This study believes that the success of rooftop solar PV implementation in isolated and remote regions is not only determined by solar energy potential, but also by the accuracy of household load planning, system economics, battery requirements, and compliance with occupational health and safety aspects. Based on that, this study developed five household electricity demand scenarios to calculate energy needs, solar PV capacity, BESS requirements, LCOE, and potential emission reductions, so that a safer, more realistic, and more sustainable rooftop solar PV installation strategy can be formulated for isolated and remote communities.

RESEARCH METHOD

Calculation of energy requirements and capacity of rooftop solar PV

The total daily energy of a household in a given scenario is calculated

$$E_{load\ (daily)} = \sum_i P_i \times t_i \text{ (kWh/day)} \quad (1)$$

$$E_{load\ (yearly)} = E_{load\ (daily)} \times 365 \text{ (kWh/year)} \quad (2)$$

Where E_{load} = power load at a certain time period (kWh); P_i = total power load of main equipment (considering the number of tools and number of people)(kW); t_i = total electricity usage of equipment (Hour or h).

The installed capacity of Rooftop solar PV (P_{PV} in kWp is calculated based on the daily energy consumption profile ($E_{load\ (daily)}$ dalam kWh/hari) divided by the total hours of effective solar irradiation (t_{avg}, the average in Indonesia is 4.5 hours/day) the average in Indonesia is 4.5 hours/day (PR, assumed an empirical average of 75%-86%, assumed to be 75%)(Damayanti et al., 2019; Pvsyst, 2026; SolarVis, 2026; Wisnu Surya Pambudi & Mufti Azis, 2025).

$$P_{PV} = \frac{E_{load\ (daily)}}{t_{avg} \times PR}\ \text{(kWp)} \tag{3}$$

$$C_{BESS} = \frac{E_{backup}}{DOD \times \eta_{sys}}\ \text{(kWh)} \tag{4}$$

Where C_{BESS} = Total installed battery capacity (kWh); E_{backup} = total energy requirements during backup time (kWh); DOD = *Depth of Discharge* for Lithium technology ($LiFePO_4$) set maximum 80%; η_{sys} = Total conversion efficiency of the inverter system (theoretical 0.95).
In short, every 1 kWh of electricity to be drawn requires a physical battery of

$$C_{BESS} = \frac{1}{0.8 \times 0.95}\ \text{(kWh)} = 1.32\ \text{kWh}$$

Rooftop PV investment costs and LCOE

The investment costs for rooftop solar PV in this study were compiled using a simple yet realistic approach so that they can be directly used as a basis for technical-economic calculations for households in the remote and isolated regions. For systems without BESS, this study used an investment cost assumption of IDR 15,000,000 per kWp with direct power utilization is estimated at a maximum of 35%. Meanwhile for systems with BESS, an investment cost assumption of IDR 28,000,000 per kWp was used (Hybrid Lithium $LiFePO_4$ with power absorption utilization is estimated at 100%.). These values were chosen as working references because they are still in line with the range of household rooftop solar power installation costs in Indonesia, which are generally at around IDR 14–20 million per kWp for basic systems without batteries, while more complete system packages can be at a higher level depending on capacity, brand, logistics, and energy storage configuration (Putu et al., 2022; Solusi Power Indonesia, 2026; Thertina, 2026; VoI, 2022).

Capital Expenditure (CapEx) consists of purchase of solar PV modules, balance of system (BoS), inverter, protection panels and installation services. The formula for the hybrid systems also has batteries and the hybrid system. Operational Expenditure (OpEx) including routine inverter maintenance will be allocated 1.5% of total CapEx annually (Firdaus & Amrina, 2025; Wisnu Surya Pambudi & Mufti Azis, 2025)*:*

$$CapEx_{Total} = \sum Cost_{PV,BoS,Installation} + \sum Cost_{BESS,Hybrid\ Inverter} \tag{5}$$

The Levelized Cost of Energy (LCOE) is the cost of generating electricity (Rp/kWh) normalized by the life of the project (n = 20 years) with a discount rate (r = 8%) and power degradation (d = 0.5% per year) for rooftop PV in a household or a communal (Damayanti et al., 2019; Pvsyst, 2026; SolarVis, 2026; Wisnu Surya Pambudi & Mufti Azis, 2025).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CapEx\ + OpEx}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{gen,t}\ \times (1-d)^t}{(1+r)^t}} \tag{6}$$

Reduction of greenhouse gas emissions ΔE_{GRK} ($\mathbf{kg\ CO_2e}$)

Emission reductions are calculated by comparing the clean energy produced by solar PV to the Emission Factor (FE) of fossil fuel power plants. For isolated diesel power

plants, FE_{PLTD} = 0.8 – 1 kg CO_2e per kWh, depending on the load factor, with an average of around 0.8 kg CO_2e per kWh (Clean Development Mechanism, 2025).

$$\Delta E_{GRK}\ (\text{kg}\ CO_2\text{e}) = E_{PLTS}(\text{kWh}) \times FE_{PLTD} \quad (7)$$

Diesel power generation costs in Indonesia vary widely by scale and location, with case study reports indicating a range of around Rp 3,269/kWh to Rp 6,656/kWh (Jaya, 2021; Lubis, 2022), while in the archipelago/isolated and remote regions a comparative value of around Rp 4,791/kWh to Rp 5,539/kWh is often used (Rianto, 2024; Supriadi & Sudiarto, 2026).

Main equipment specification assumptions

Table 1. Technical Assumptions of Equipment, Technical Specifications, Quantity, and Duration of Use

Equipment Name	Specification (P_i)	Amount	Duration (t_i)	$E_{load\ (daily)}$
LED lights	12 W	8	14 hours/day (17.00–07.00)	1.34 kWh/day
Energy-saving 2-door refrigerator	±150 W *duty cycle ~35%*	1	24 hours/day	±1.26 kWh/day
Charging smartphone	10 W	1	3 hours/day, 2 kali/hari	0.06 kWh/day per person
43" LED TV	±80 W	1	8 hours/day	±0.64 kWh/day
Fan	±45 W	2	16 hours/day	±1.44 kWh/day
Laptop	60 W	1	4 hours/day	0.24 kWh/day
WiFi Modem (cable/portable)	10 W	1	24 hours/day	0.24 kWh/day
Well pump	250 W	1	1 hours/day	0.25 kWh/day

Source: Estimation from Author analysis from daily life and market observation (Marwan, 2026; Massagony et al., 2026; Panasonic, 2026; Yani, 2025)

In solar PV design, the daily load is the primary basis for calculating panel capacity and energy storage requirements; if the load is assumed too low, the system will be underpowered, while if it is too high, it will be cost-inefficient. Therefore, the assumptions in Table 1 should be read as a conservative and operational load profile for households already using modern basic appliances.

Household load scenarios

Five load scenarios are arranged as follows (with $\boldsymbol{N = 1, 2, 3\ and\ 5\ people}$):

1. Scenario 1: LED lights + refrigerator + smartphone charging for $\boldsymbol{N\ people}$.
2. Scenario 2: Scenario 1 + LED TV
3. Scenario 3: Scenario 2 + 2-Fans
4. Scenario 4: Scenario 3 + Wi-Fi
5. Scenario 5: Scenario 4 + well pump + laptop charging (1 unit for all of $\boldsymbol{N = 1, 2, 3\ and\ 5\ people}$)

The daily energy consumption is calculated by adding together the energy consumption of each appliance and converting them into monthly and yearly consumption. Scenario 1 represents the current basic needs such as lighting, cooling and communication media such as smart phones. Scenario 3 is medium basic needs and Scenario 5 is ideal living conditions that meet the needs of internet-based or distance learning and information.

RESULTS AND DISCUSSION

Daily energy per scenario

The dimensioning accuracy of the electrical system is simulated through 5 nested scenarios as described in **Section 2.6.** which are adapted specifically for energy-saving devices, based on the interaction of the household occupants, with the number of people: $\boldsymbol{N = 1, 2, 3\ and\ 5\ people}$

Table 2. Daily Electrical Energy Consumption ($E_{load\ (daily)}$) based on $\mathbf{N = 1, 2, 3\ and\ 5\ people}$

Condition	$E_{load\ (daily)}$(kWh/day)			
	$N = 1$	$N = 2$	$N = 3$	$N = 5$
Scenario 1	2.66	2.72	2.78	2.90
Scenario 2	3.30	3.36	3.42	3.54
Scenario 3	4.74	4.80	4.86	4.98
Scenario 4	4.98	5.04	5.10	5.22
Scenario 5	5.47	5.53	5.59	5.71

Based on five tiered household consumption scenarios, daily electricity load shows a consistent increase as the number of appliances and household activity requirements increase. In the lowest scenario, energy demand is 2.66–2.90 kWh/day, while in the highest scenario, it reaches 5.47–5.71 kWh/day, depending on the number of occupants. This pattern indicates that basic household needs in the remote and isolated regions can actually still be met by small-scale solar power systems, provided the load design is carried out in a disciplined and efficient manner.

Cost Estimation and LCOE Performance Analysis of Rooftop solar PV (BESS vs Non-BESS)

Implementing the design formula, the CapEx price is determined based on the domestic market:

Table 3. Physical Requirements for PV Capacity (P_{PV})()(kWp) based on $\boldsymbol{N = 1, 2, 3, dan\ 5\ orang}$

Condition	P_{PV} (kWp)			
	$N = 1$	$N = 2$	$N = 3$	$N = 5$
Scenario 1	0.79	0.81	0.82	0.86
Scenario 2	0.98	1.00	1.01	1.05
Scenario 3	1.41	1.42	1.44	1.48
Scenario 4	1.48	1.49	1.51	1.55
Scenario 5	1.62	1.64	1.66	1.69

Based on the solar PV capacity calculations, the system's physical requirements range from 0.79 to 1.69 kWp. Scenario 1 requires 0.79 to 0.86 kWp, while Scenario 5 requires 1.62 to 1.69 kWp, depending on the number of occupants. This means that a household with efficient consumption can still be served by a relatively small PV system, as long as the load configuration and operating hours are well designed.

Capacity increases from scenario to scenario are primarily driven by the addition of appliances such as TVs, fans, laptops, Wi-Fi modems, and water pumps. This means that solar PV capacity does not simply depend on the number of occupants, but is more influenced by the complexity of lifestyles and the level of demand for basic services. Therefore, this scenario-based approach is more realistic than a uniform capacity approach for all households.

Table 4. Financial Analysis Matrix and Levelized Cost of Energy (LCOE)

Load Scenario $N = 3$	P_{PV} (kWp)	$CapEx_{Total}$ $(no\ BESS)$ (Rp)	$LCOE$ $(no\ BESS)$ (Rp/kWh)	$CapEx_{Total}$ $(+BESS)$ (Rp) (Rp)	$LCOE$ $(+\ BESS)$ (Rp/kWh)
Scenario 1	0.82	12,300,000	1,475	22,960,000	2,753
Scenario 2	1.01	15,150,000	1,476	28,280,000	2,756
Scenario 3	1.44	21,600,000	1,481	40,320,000	2,765
Scenario 4	1.51	22,650,000	1,480	42,280,000	2,764
Scenario 5	1.66	24,900,000	1,485	46,480,000	2,772
Note: Interest rate = 8%, project life = 20 years, OpEx = 1.5% of CapEx per year. Not considering transportation and logistics costs during project life.					

The cost analysis results show that a system without BESS has a lower LCOE, around IDR 1,475–1,485/kWh, with a total CapEx of around IDR 12.3 million to IDR 24.9 million, depending on the scenario. Conversely, a system with BESS requires an investment of around IDR 23 million to IDR 46.5 million, with an LCOE of around IDR 2,753–2,772/kWh. This difference confirms that while batteries improve reliability, they also increase the initial cost and the cost of the energy produced.

However, economic interpretation should not be limited to LCOE figures alone. In an on-grid context with a zero-export policy and the elimination of net metering, the value of batteries increases because they help absorb daytime production and shift it to the nighttime. Meanwhile, in an off-grid or weak grid context, BESS becomes a strategic element in maintaining supply continuity and reducing reliance on diesel.

Communal Economic Analysis

To understand the feasibility of solar PV (rooftop PV) on a larger, decentralized scale—such as communal implementation in remote and isolated regions—it is necessary to extrapolate the load and compare it with conventional electricity solutions, namely diesel-fired power plants (PLTD)

PLTDs remain the backbone of energy supply in small islands in Indonesia due to their ease of initial installation. However, PLTD operational costs are very high due to high specific fuel consumption (SFC), high logistics costs for transporting diesel fuel to remote and isolated regions, and high mechanical maintenance costs. Based on aggregate data from PT PLN (Persero), the LCOE for small- to medium-scale PLTDs, is currently high, averaging Rp 4,791/kWh. From the environmental perspective, the burning of diesel fuel in PLTDs emits a significant quantity of greenhouse gases (GHG). The GHG emission factor for isolated grids, e.g. diesel power plants in remote and isolated regions, is estimated to average 0.8 kg CO_2e per kWh of electrical energy generated. Power requirements extrapolated from the Scenario 5, $N = 3\ people$ with 5.59 kWh/from/house shown in **Table 4**.

Table 5. Extrapolation of Communal Energy Needs and GHG Emission Reduction (PV vs. PLTD) - Representation of Scenario 5, $N = 3$

Communal Scale	E_{load}			Estimate			
	$Daily$ (kWh)	Yearly (kWh)	P_{PV} (kWp)	$LCOE$ $(No\ BESS)$ (Rp/kWh)	$LCOE$ $(+\ BESS)$ (Rp/kWh)	$LCOE$ Diesel Power Plant	ΔE_{GRK} $(\mathrm{kg}\ CO_2\mathrm{e})$ per year

						(Rp/kWh)	
1 House	5.59	2,040.4	1.66	1,485	2,772	4,791	1,632.3
3 Houses	16.77	6,121.1	4.98	1,455	2,716	4,791	4,896.8
5 Houses	27.95	10,201.8	8.30	1,425	2,661	4,791	8,161.4
10 Houses	55.90	20,403.5	16.60	1,366	2,550	4,791	16,322.8
20 Houses	111.80	40,807.0	33.20	1,277	2,383	4,791	32,645.6
50 Houses	279.50	102,017.5	83.50	1,188	2,217	4,791	81,614.0
Note: Assuming 1 household = 5.59 kWh/day = 2,040.4 kWh/year. The BESS safety factor is set at 1.5 of the total daily load. The emission reduction is calculated using a diesel power plant emission factor of approximately 0.8 kg CO_2e/kWh.							

Extrapolating to the communal scale, a clear decrease of LCOE with the number of households is visible. The LCOE with BESS for a single household in the community is around IDR 2,772/kWh and for 50 households it is reduced to around IDR 2,217/kWh. This pattern is an example of economies of scale. Fixed costs (mobilization, permitting and installation) can be spread over a larger number of users, leading to a lower cost per kWh.

Communal solar PV are far more competitive than diesel powered plants (PLTD) with LCOE estimated of around IDR 4,791/kWh. The substitution of diesel power plants with rooftop PV at the level of 50 households can bring about a large reduction in energy costs and eliminate more than 81.6 tons CO_2e per year. This makes communal solar PV cleaner and also a more financially viable option for remote and isolated regions.

Analysis of Implementation Strategies in Indonesia: Electrification Pilots in Priority Villages

Linsayung Village in Lumbis Ogong District, Nunukan, and Long Berang Village in Mentarang Hulu District, Malinau, can serve as examples because they represent very different, yet equally strategic, isolated and remote contexts. Linsayung has approximately 19 homes with 60 residents, while Long Berang has approximately 87 homes, although the latest data still needs to be verified before final design (Dinas ESDM, 2026; Kompas TV, 2025). These two villages are important because they demonstrate two contrasting scales of implementation: a small scale suitable for a limited household-communal approach and a larger scale requiring a more structured micro-grid strategy. If rooftop solar PV can succeed in these two villages, their models have the potential to serve as a reference for other remote and isolated regions facing similar challenges: expensive electricity access, challenging logistics, and reliance on inefficient diesel generators.

From Table 6, it can be seen that the most realistic scenario for the initial plan in Linsayung Village and Long Berang Village is Scenario 3 and Scenario 5 with a base of $\boldsymbol{N = 3\ people}$, resulting in an estimated load per household of 4.86 kWh/day and a solar PV capacity of about 1.44 kWp. This value confirms that household electricity needs in remote and isolated regions can still be served by a relatively small solar PV system, provided the load is arranged economically and in stages. However, this data also provides an important message that system design is not enough to look only at capacity figures, but

must also consider daily usage patterns, installation quality, and community readiness so that the system built can truly be used stably and does not incur excessive costs.

Table 6. Analysis of Rooftop solar PV Strategy in Linsayung Village and Long Berang Village, North Kalimantan

Village	**Basic data used**	**Assuming Scenarios**	**Estimated load per house (kWh/day)**	**Estimated solar PV rooftop capacity per house (kWp)**
Linsayung Village, Lumbis Ogong, Nunukan.	19 houses	Scenarios 3 and 5, $\boldsymbol{N = 3}$	4.86-5.59	1.44-1.66
Long Berang Village, Mentarang Hulu, Malinau.	87 houses	Scenarios 3 and 5, $\boldsymbol{N = 3}$	4.86-5.59	1.44-1.66
Note: Does not include public facilities or private assets designated as public facilities.				

Table 7. Analysis of Communal Rooftop solar PV Implementation Strategy in Linsayung Village and Long Berang Village – Representation, $\boldsymbol{N = 3\ people}$

Village	**Base scenario**	**Daily energy (kWh/day)**	**Annual energy (kWh/year)**	$\boldsymbol{P_{PV}}$ **(kWp)**	$\boldsymbol{LCOE\ (No\ BESS)}$ **(Rp/kWh)**	$\boldsymbol{LCOE\ (+\ BESS)}$ (Rp/kWh)	**Potential** $\boldsymbol{\Delta E_{GRK}}$ $\boldsymbol{(\mathrm{kg}\ CO_2\mathrm{e})}$ **per year**
Linsayung	Scenario 3	92.34	33,704.1	27.36	1,281	2,391	26,963.3
Linsayung	Scenario 5	106.21	38,766.7	31.54	1,284	2,397	31,013.3
Long Berang	Scenario 3	422.82	154,329.3	125.28	1,110	2,073	123,463.4
Long Berang	Scenario 5	486.33	177,510.5	144.42	1,113	2,079	142,008.4

The results in Table 7 show a significant difference in impact between the two villages. In Linsayung Village, the baseline scenario of Scenario 3 produces 92.34 kWh/day or 33,704 kWh/year of communal energy, a communal solar PV capacity of 27.36 kWp, an LCOE with BESS of approximately IDR 2,391/kWh, and a potential emission reduction of 26,963.3 kg CO_2e per year, while in Scenario 5 the figures increase to 106.21 kWh/day, 38,766.7 kWh/year, 31.54 kWp, and an emission reduction of 31 ton CO_2e per year. In Long Berang Village, the scale of impact is much greater: Scenario 3 reaches up to 422.82

kWh/day or 154,329.3 kWh/year with a solar PV capacity of 125.28 kWp and an emission reduction of 123,463.4 kg CO_2e per year, while Scenario 5 increases up to 486.33 kWh/day, 177,510.5 kWh/year, 144.42 kWp, and an emission reduction of more than 142 ton CO_2e per year. These figures show that the larger the number of homes and the basic service load, the greater the economic and environmental benefits that can be achieved, but at the same time, considerations of initial investment, BESS reliability, and operational governance are increasingly important for the implementation of rooftop solar PV to be truly sustainable.

Analysis of Regulations and Legislation in implementation

Table 8. Regulatory gap analysis

Aspect	Regulations/Legislation that already support	The gap that still exists	What needs to be encouraged
Direction of energy transition policy	Presidential Decree No 112/2022 provides a wider policy base and accelerates renewable energy.	Policy targets and support have not always translated into simple implementation mechanisms on the ground.	It is necessary to synchronize national targets with regional implementation schemes, especially remote and isolated.
Economic scheme of rooftop solar power	Rooftop household solar PV are still possible, but their orientation is now more towards self-consumption because the electricity import-export scheme to the grid has changed.	Household economic security has become weaker, especially for users who previously relied on electricity buying and selling schemes.	There has to be more incentives, subsidies or financing models for communities and households.
Installation and safety standards	PUIL 2011/SNI 0225:2011 is a reference for low voltage electrical installations, and the Directorate General of Gatrik has socialized the technical standards for Gatrik rooftop PV.	Implementation in the field is still often hampered by installation quality, DC protection, and uneven technical compliance.	There is a need for more specific, simpler, and easily auditable technical standardization for local installers.
Occupational health and safety	The occupational health and safety aspect has been recognized as an important part in the implementation of rooftop solar PV.	Not all projects have robust and uniform inspection, commissioning and maintenance procedures.	There is a need for mandatory occupational health and safety audits, installer certification, and

Aspect	Regulations/Legislation that already support	The gap that still exists	What needs to be encouraged
			standard occupational health and safety SOPs.
remote and isolated and off-grid regions	Renewable energy policies generally support equal access to energy in underdeveloped regions.	Very specific regulations for communal solar PV, micro-grids, and off-grid in remote and isolated are still limited.	Special regulations are needed for communal models, local institutions, and long-term operational schemes.
Financing	The renewable energy policy framework already provides space for accelerating renewable energy investment.	There is still a gap in high initial financing, especially when using BESS.	There is a need for soft financing schemes, initial grants, or blended financing for remote and isolated.
Transitional justice	Renewable energy policies are starting to move towards a broader energy transition.	The aspects of social justice, community involvement, and user protection are not yet strong enough in technical regulations.	A fair, participatory, and locally needs-based approach to the energy transition is needed.

Table 9. Conclusions from the Regulatory Gap Analysis

Regulatory conclusions	Explanation
Already supported	The basic legal framework for rooftop solar PV, renewable energy, and installation occupational health and safety is already in place.
Still not enough	Technical regulations, financing, and implementation models for remote and isolated regions are not yet detailed enough.
Need to be encouraged	Derivative regulations for communal solar PV, more operational occupational health and safety standards, and fairer incentive and financing schemes.

In general, existing regulations have provided a strong foundation for promoting rooftop solar PV, from ESDM Ministerial Regulation No. 2 of 2024 as the primary umbrella, Presidential Regulation No. 112 of 2022 as a reinforcement of the energy transition direction, to PUIL 2011 and electricity technical standards as a reference for installation safety. However, the most important highlight of the table is the continued significant gap in implementation, particularly in the remote and isolated regions, as existing regulations do not sufficiently detail the communal solar PV model, affordable financing, operational occupational health and safety standards in the field, and long-term institutional and maintenance mechanisms. Therefore, what is most urgently needed is not only new regulations but also more practical, equitable, and easily implemented policy derivatives to ensure rooftop solar PV are truly safe, economically viable, and relevant to Indonesia's diverse context.

SWOT analysis

Table 10. SWOT Analysis of Rooftop PV Implementation Strategy in Remote and Isolated Regions

Main Point	Analysis
Strength	• Rooftop solar PV is suitable for remote and isolated regions as they are modular, quick to install and don't require long transmission lines. • Operating costs are much lower than diesel power plants, especially for communal systems. • Greenhouse gas emissions can be significantly reduced, aligning with the decarbonization agenda.
Weakness	• The initial investment is huge, especially with BESS. • The reliability of the system is strongly affected by the quality of the installation and follow-up maintenance. • The intermittency of solar production requires good load management.
Opportunity	• The remote and isolated electrification program and energy transition targets offer opportunities for widespread uptake. • Communal scale can reduce the LCOE and speed up energy access. • Opportunities to grow regional economies through local installer development, vocational training and component supply chains.
Threat	• Extreme weather, coastal corrosion and high humidity can speed up system degradation. • Fires and loss of public confidence due to failure to meet safety standards. • Policy or quota limitations may change and this may affect the viability of projects in grid-connected regions.

Implementation strategy for remote and isolated regions

If this system is implemented across Indonesia, the approach cannot be uniform. Island and coastal regions require special attention to corrosion, strong winds, high humidity, and expensive logistical access. Mountainous regions need to consider roof slopes, potential shading, and equipment transportation limitations.

The most rational strategy remote and isolated regions is a phased approach based on basic services. The first phase prioritizes essential loads: LED lights, smartphone charging, fans, small TVs, and efficient water pumps; the second phase adds productive household appliances if the generation profile and affordability are adequate. BESS should be prioritized only in two situations: poor grid quality or households urgently need a reliable nighttime supply for basic services. When the PLN grid is relatively stable, a strategy without

BESS, with load shifting to daytime, is usually more economical because the elimination of net metering makes the added value of batteries more dependent on reliability, rather than simply bill savings.

In regions still reliant on diesel power plants, the communal model is highly recommended due to its greatest economic benefits. Meanwhile, in regions with the PLN grid, designs should emphasize self-consumption, daytime load regulation, and truly needs-based BESS selection. For urban or semi-urban regions, regulatory compliance, building structure, and installation reliability are the key determinants of success.

Discussion of Occupational Health and Safety Aspects Needs

The implementation of rooftop solar PV in remote and isolated regions often clashes with low awareness of occupational health and safety standards. Based on technical findings, several essential needs analyses related to this implementation are available:

Table 11. The Occupational Health and Safety Aspects Needs Analysis in Rooftop PV Implementation in Remote and Isolated Regions

Main Point	Analysis
Direct Current (DC) Hazard Protection	• The system must be equipped with DC Ground Fault detection and use a very tight MC4 crimping connector connection. • Non-compliance with SNI 0225:2020 Section 7-712 will trigger a dangerous DC arc-fault issue that can burn down building structures.
Electrical Component Integrity	• The selection of electrical materials such as the use of flame retardant type cables and voltage protective combiner boxes must be absolute parameters in designing the Bill of Quantities (BoQ) of the BESS system.
Building Civil Resilience Audit	• Considering that solar modules will add a static load of tens to hundreds of kilograms, civil evaluation and audit of the roof frame structure of the installation site must be carried out strictly before installation.
Tropical Weather Resistance	• Considering that solar modules will add a static load of tens to hundreds of kilograms, civil evaluation and audit of the roof frame structure of the installation site must be carried out strictly before installation.

Tropical humidity and thermal radiation severely test the physical integrity of roof installations. Failure to comply with SNI 0225:2020 Section 7-712 regarding the tightness of the MC4 DC connector connections and the absence of DC Ground Fault protection will open the door to the disaster of a DC arc-fault that can burn down the entire house. Furthermore, regulations indirectly dictate the importance of civil audits of the supporting frame, considering that the panel load is equivalent to an additional tens to hundreds of kilograms on top of the roof frame of a commercial residence.

Discussion of Professional Ethics Aspects

Professional ethics in the implementation of rooftop solar PV in remote and isolated regions is not only about the adherence to technical procedures but also a moral responsibility to ensure that the installed system is truly safe, feasible and of benefit to the community. Principles such as integrity, competence, professional due care and objectivity are key to ensure that system designers, installers and managers do not make decisions based solely on cost efficiency but also consider user safety, installation quality, and long-term risks to homes and the environment (Muhaini et al., 2024). In remote villages,

professionalism also means not overestimating what the system can do, not oversimplifying the requirements in the field, and not hiding technical limitations that could affect the reliability of the electricity supply (Muhaini et al., 2024).

Professional ethics is also reflected in the respect the professionals have for the community as the end users of the technology. People in the villages of Linsayung, Long Berang and other villages should be entitled to get the truth on the capacity of the system, investment cost, maintenance cost, risk of using batteries and also the limitation of rooftop solar PV to meet the daily load. Technical communication should therefore be transparent and easily understood, and should not raise false expectations (Sukoco & Widiastuti, 2021). It is a professional ethics that all parties involved openly explain the assumptions of the calculations (irradiation parameters, performance ratios, CapEx and OpEx costs, emission factors) so that the public and policy makers can reasonably judge the benefits of the system (Muhaini et al., 2024; Sukoco & Widiastuti, 2021; Zuhri, 2010).

Finally, professional ethics calls for concern for social justice and safety. In energy projects in remote and isolated regions, wrong technical decisions cause economic losses and damage households that rely on electricity for basic needs such as lighting, communication and small economic activities (Sukoco & Widiastuti, 2021; Zuhri, 2010). Therefore, professionals need to ensure that system designs take into account local conditions, user capacity, and operational readiness so that implementation not only looks good on paper but can actually be run sustainably. With this approach, professional ethics becomes part of the project's quality, not merely an administrative add-on.

CONCLUSION

The results of this study demonstrate that the installation of rooftop solar PV for households in the remote and isolated region is worth considering for more effective, clean and adaptive electrification solution for remote and isolated regions. The household energy needs are computed as 2.66–5.71 kWh/day with the required capacity for the PV power plant of about 0.79–1.69 kWp. So a relatively small system can indeed meet basic household electricity needs if the load is designed in an efficient and incremental manner. In terms of cost, the system without BESS is still cheaper with LCOE of around IDR 1,475–1,485/kWh; whereas the system with BESS is in the range of IDR 2,753-2,772 especially for nighttime or off-grid regions.

Broadly, the findings from the study demonstrate that communal implementation has much greater economic and environmental impact. The LCOE for Scenario 5 with $\boldsymbol{N = 3\ people}$ of a rooftop PV with BESS drops from approximately IDR 2,772/kWh for one household to approximately IDR 2,217/kWh for 50 households, significantly lower than the electricity cost of a diesel-powered plant (PLTD), which reaches IDR 4,791/kWh. The potential emission reductions could reach up to 81,614.0 kg CO_2e per year. The results suggest that the scale of such systems, the need for energy storage, the local electricity service conditions and the compliance with occupational health and safety aspects, not only the capacity and investment costs, should be taken into account in their implementation, so that the system is economical, safe, reliable and sustainable in the long term.

Future research should extend the analysis by studying field data in other typologies in Indonesia, such as coastal regions, mountainous regions, small islands and regions with limited PLN (State Electricity Company) networks to obtain more contextual design models and implementation strategies. Further studies are also needed to evaluate the lifetime of the system, the cost of replacing batteries, the trends in maintenance, and the acceptance by the community in order to better understand the long-term viability of rooftop PV.

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